Rheology of the Quark Gluon Plasma

# Measurement of the QGP Shear Viscosity with $p_t$ $p_t$ Correlations in Heavy Ion Collisions

Claude A. Pruneau and Monika Sharma, for the STAR Collaboration
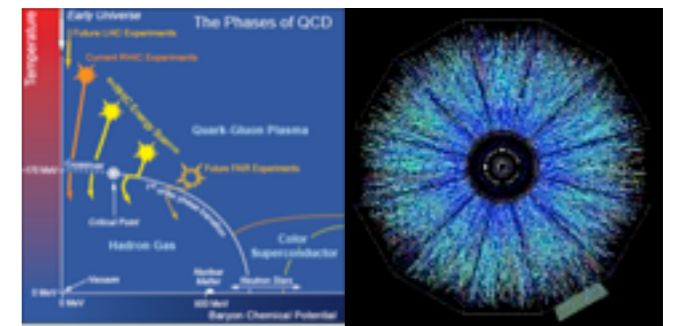
**WAYNE STATE UNIVERSITY**

- Is the QGP a Perfect Fluid ?
- New Technique/Observable to estimate the viscosity
- Modeling with EPOS, AMPT, HIJING, and SPHERIO
- Measurement in Au + Au at 200 GeV

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# Is the sQGP a Perfect Fluid?

- Superfluid Helium
- Ultra Cold Gasses (few nK)

- Quark Gluon Plasma
  T~200 MeV~$10^{12}$ K
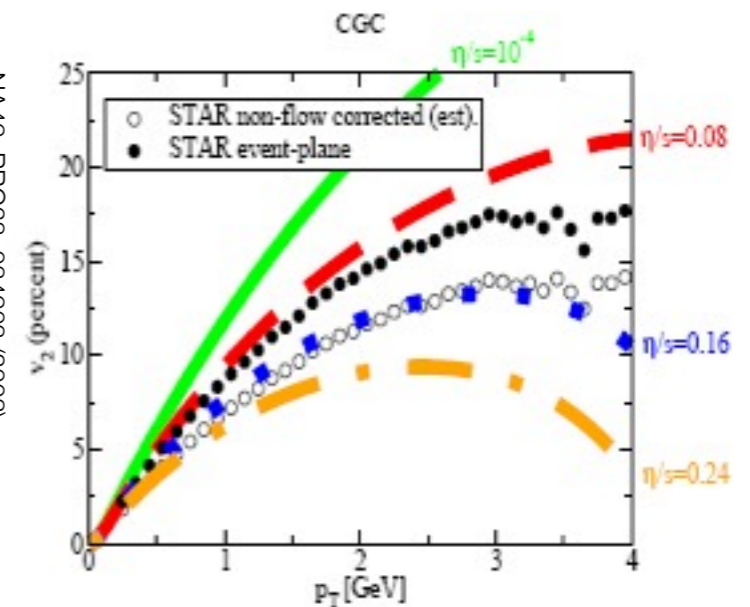  Temperature of early universe at ~1 micro-sec
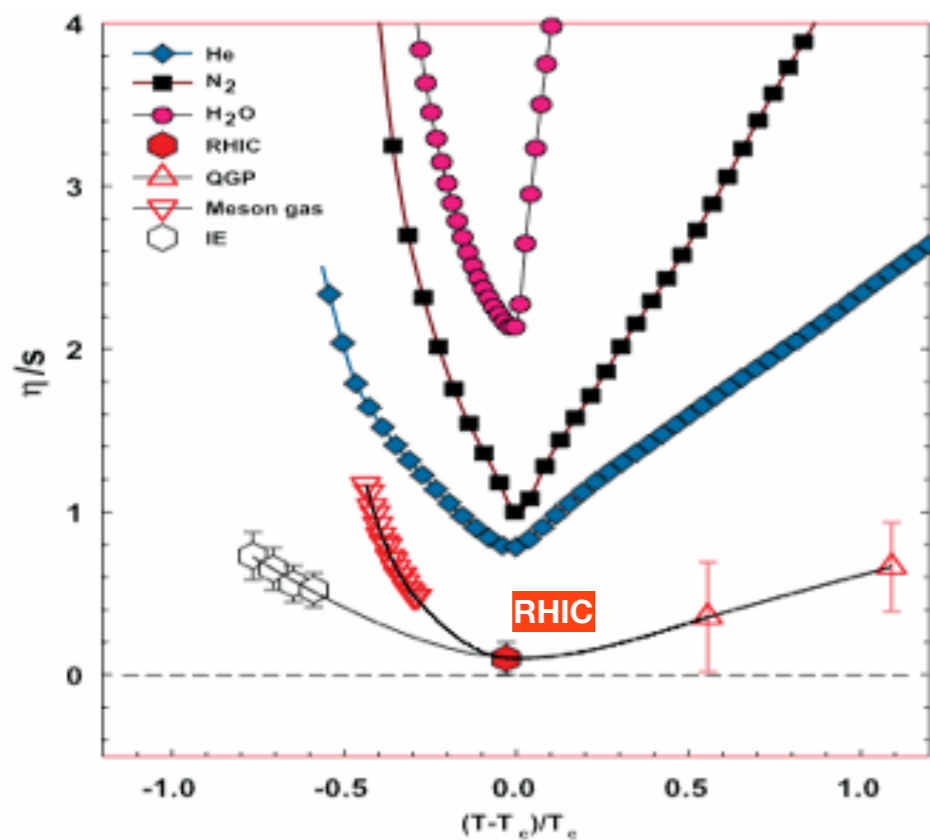
Conjectured low bound of shear viscosity/entropy:

Supersymmetric Yang Mill Theory (Ads/CFT duality
Kovtun, Son, & Starinets, PRL94(2005)

$$\frac{\eta}{\hbar s} \geq \frac{1}{4\pi}$$

*M. Luzum & P. Romatschke, 0804.4015; 0901.4588*

*H. Song & U. Heinz 0805.1756v2*

*P. Huovinen*

# Is the sQGP a Perfect Fluid?

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- **Ultra Cold Gasses (few nK)**

- **Quark Gluon Plasma**
  T~200 MeV~$10^{12}$ K
  Temperature of early universe at ~1 micro-sec







*M. Luzum & P. Romatschke, 0804.4015; 0901.4588*



**Can we measure the viscosity by other means at RHIC?**

viscosity/entropy:
Supersymmetric Yang Mill Theory (Ads/CFT duality
Kovtun, Son, & Starinets, PRL94(2005)
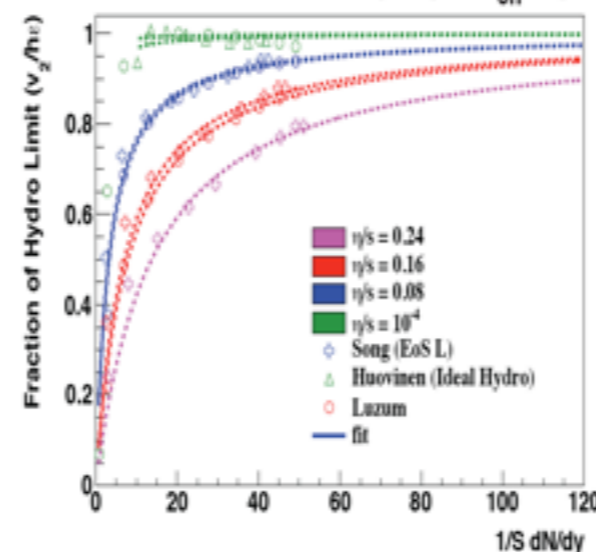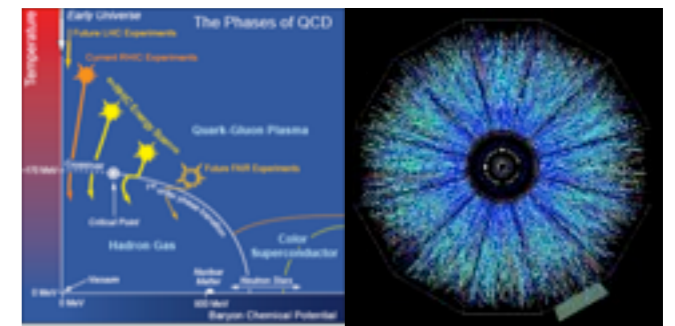
$$\frac{\eta}{\hbar s} \geq \frac{1}{4\pi}$$

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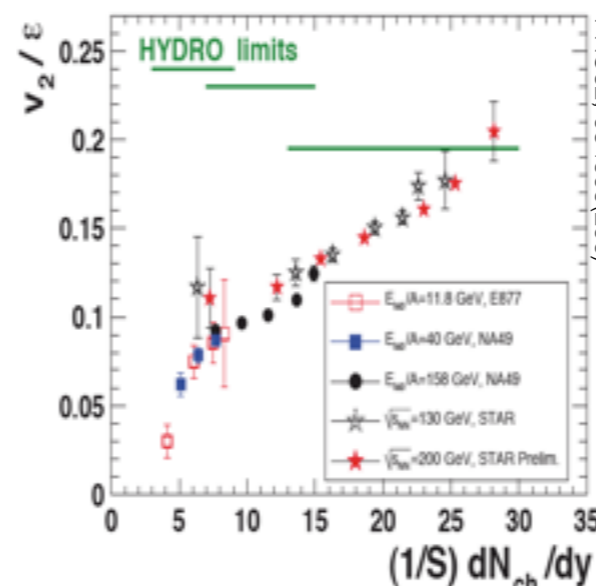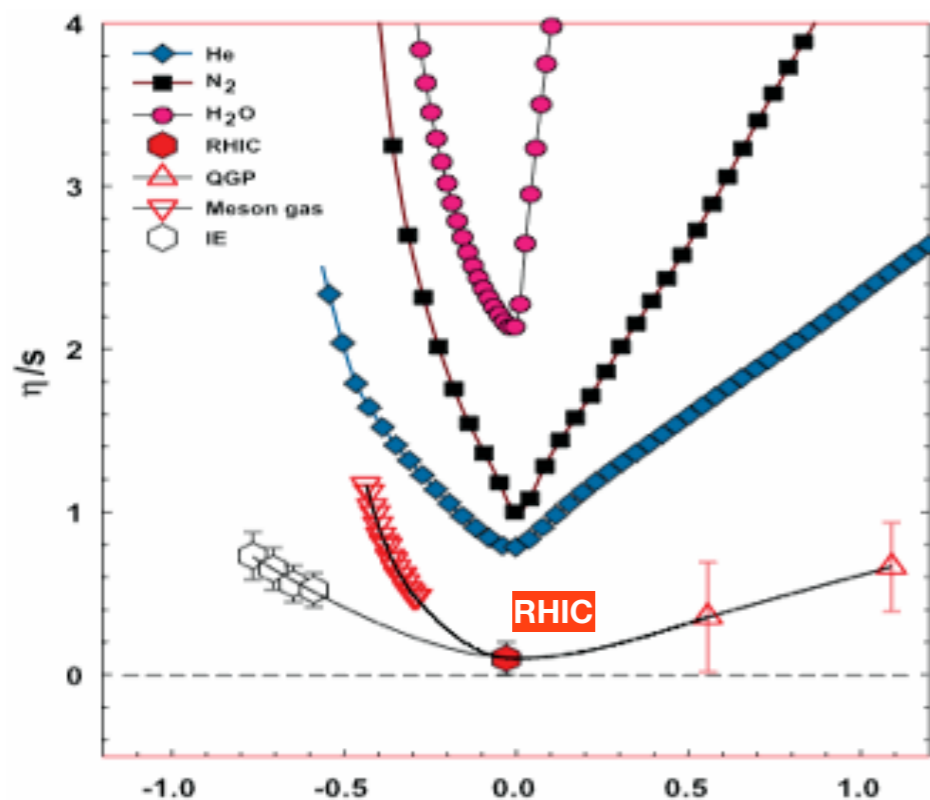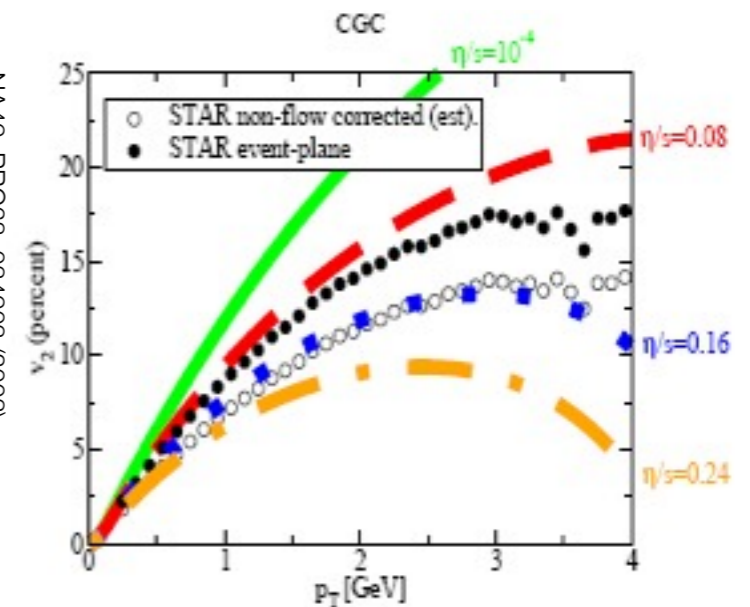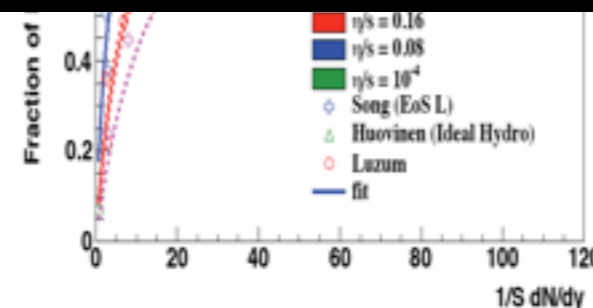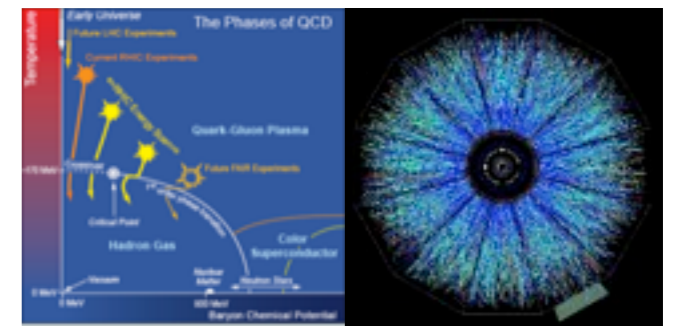
# Is the sQGP a Perfect Fluid?

- Superfluid Helium
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- Quark Gluon Plasma
  T~200 MeV~$10^{12}$ K
  Temperature of early universe at ~1 micro-sec



RHIC

HYDRO limits

$E_{kin}$ (A=11.8 GeV, E877
$E_{kin}$ (A=40 GeV, NA49
$E_{kin}$ (A=158 GeV, NA49
$\sqrt{s_{NN}}$=130 GeV, STAR
$\sqrt{s_{NN}}$=200 GeV, STAR Prelim.
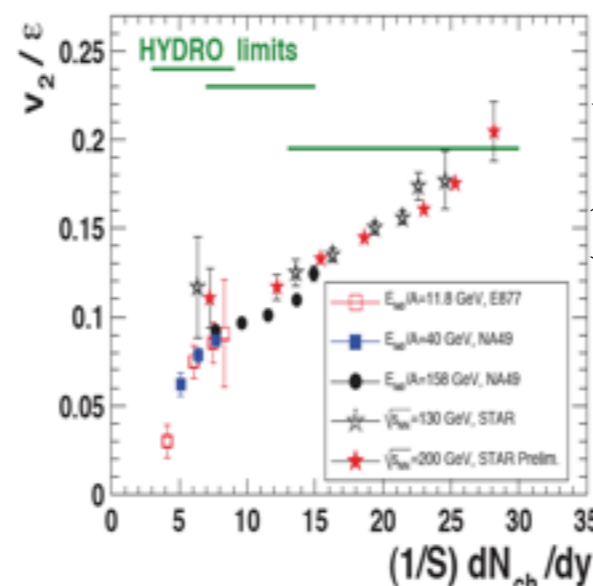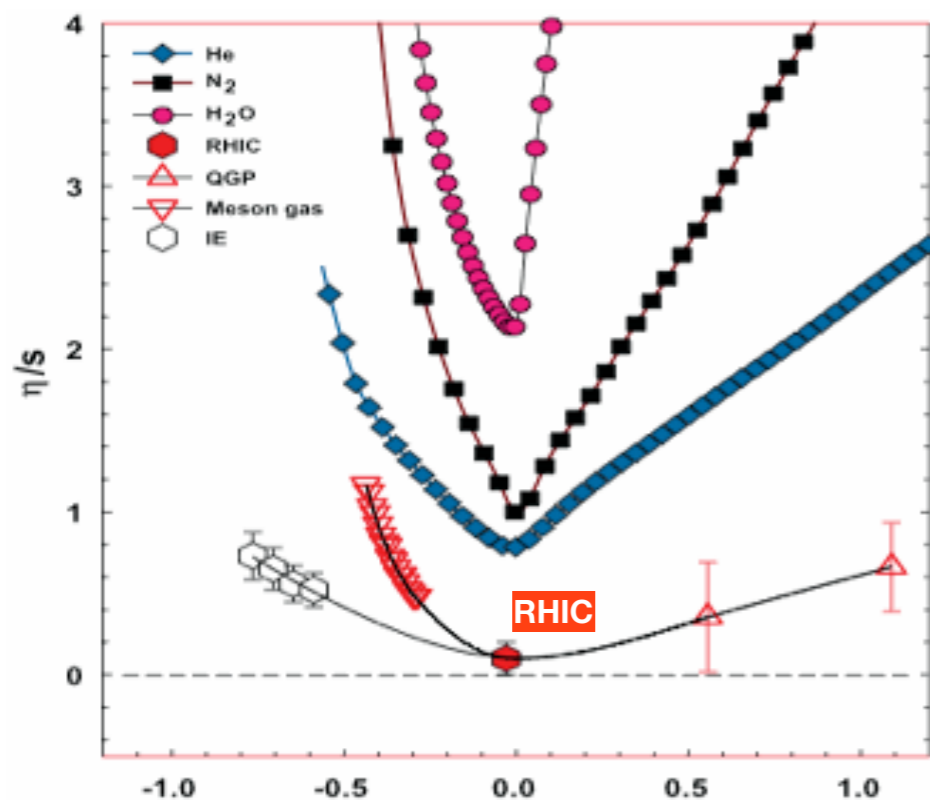
NA49, PRC68, 034903 (2003)
P.F. Kolb, J. Sollfrank, U.W. Heinz,
PRC62, 054909(200)

CGC
- STAR non-flow corrected (est).
- STAR event-plane

$\eta/s=10^{-4}$
$\eta/s=0.08$
$\eta/s=0.16$
$\eta/s=0.24$
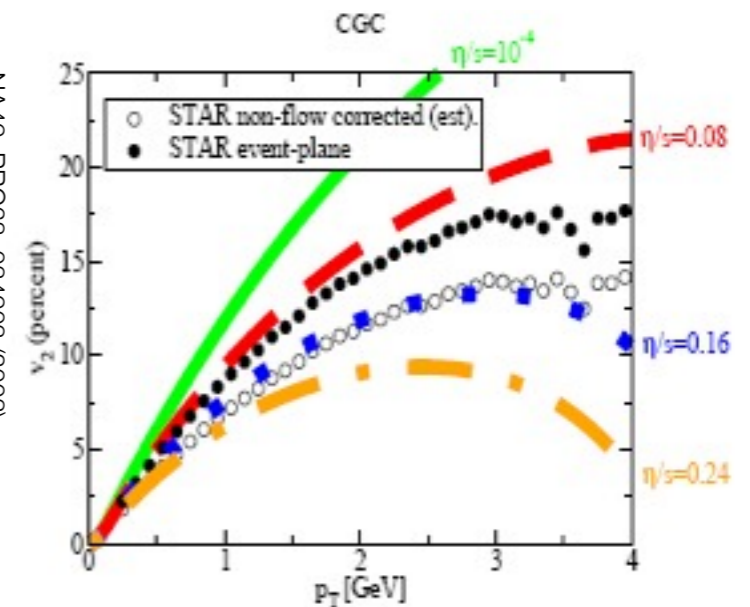
*M. Luzum & P. Romatschke,
0804.4015; 0901.4588*

**Can we measure the viscosity by other means at RHIC?**

**Yes: Use $p_t p_t$ 2-particle correlations**

Kovtun, Son, & Starinets, PRL94(2005)

$$\frac{\eta}{\hbar s} \geq \frac{1}{4\pi}$$

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# Rheometry: Measurement of Shear Viscosity
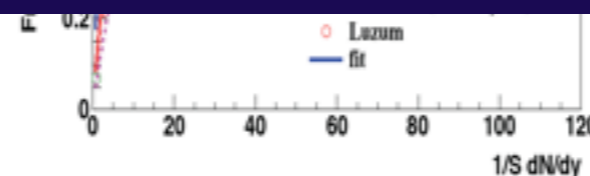
- Stress vs Deformation $\quad \tau = \eta \dfrac{du}{dy}$

  - Velocity Gradient (m/s): $\quad du/dy$

  - Shear Stress (Pa): $\quad \tau$

  - Dynamic viscosity (Pa s): $\quad \eta$

- Kinematic Viscosity (m²/s): $\quad \nu = \dfrac{\eta}{\rho}$

  - Density (kg/m³): $\quad \rho$

- Relation to the Mean Free Path (m): $\quad \nu = \dfrac{1}{2}\bar{u}\lambda$

- Stress energy tensor: $\quad T_{yx} = -\eta\dfrac{dv_x}{dy}$

- Effective Reynolds number: $\quad \mathrm{Re} = \dfrac{3}{4}\dfrac{\tau_o Ts}{\eta}$



boundary plate (2D) (moving)

velocity, $u$

shear stress, $\tau$

Fluid

gradient, $\dfrac{\partial u}{\partial y}$

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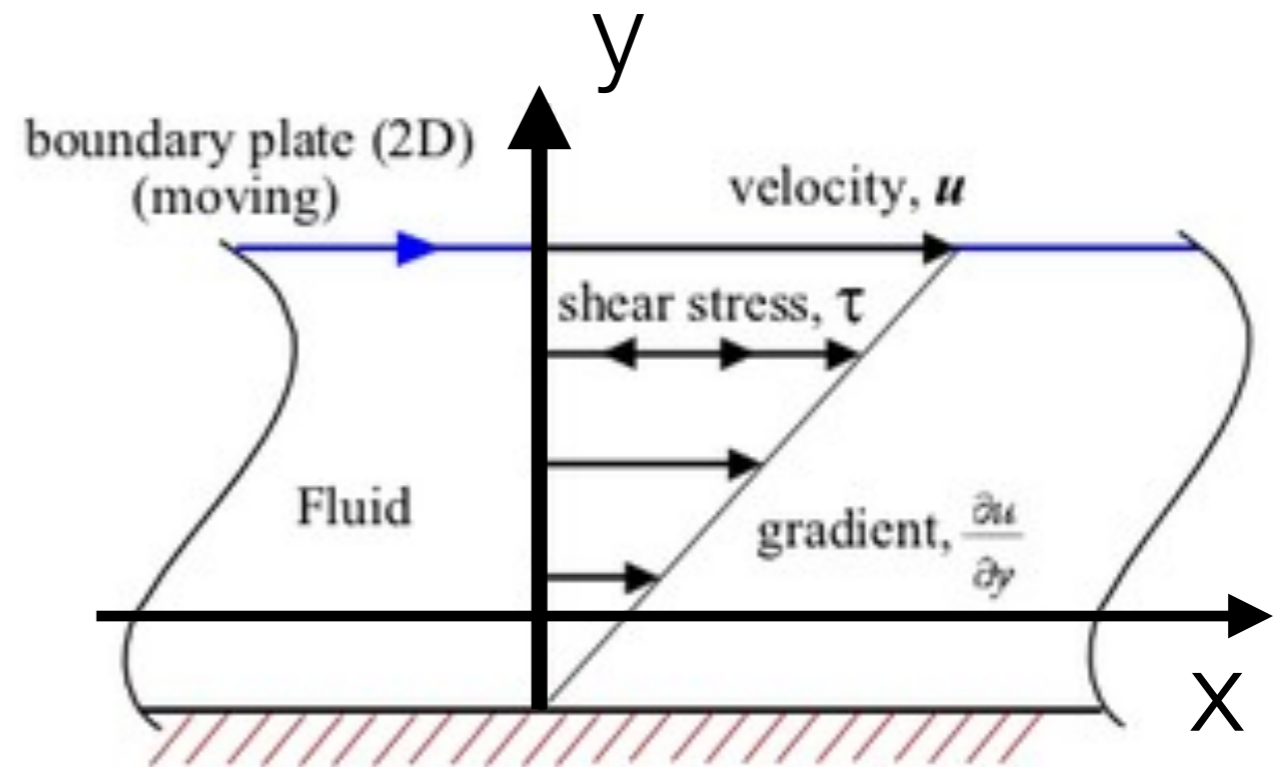
# Measurement of viscosity based on $p_t\,p_t$ Correlations

Gavin and Abdel-Aziz, nucl-th/0606061 (2006)

- Viscous friction
  - Arises as fluid elements flow past each other thereby reducing their relative velocity: damping of radial flow fluctuations.
  - Viscous friction changes the radial momentum current of the fluid
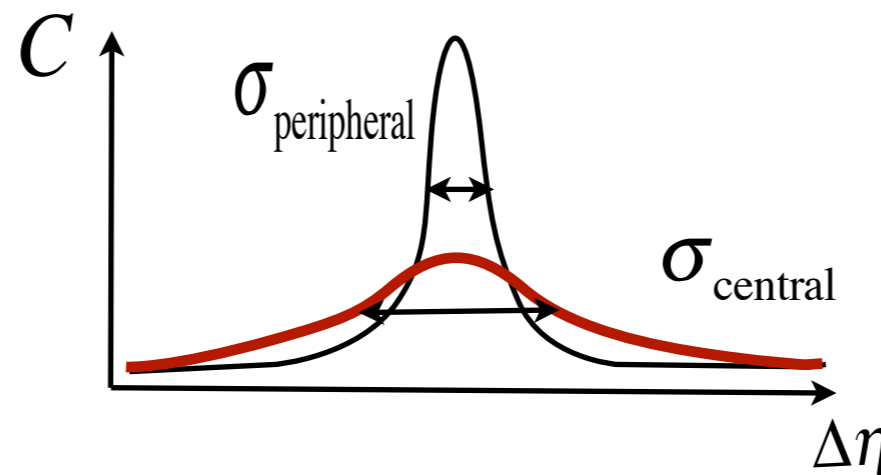  - Reduces fluctuations, distributes excess momentum density over the collision volume: broadens the rapidity profile of fluctuations
- Width of momentum correlation grows with diffusion time (system lifetime) relative to its original/initial width
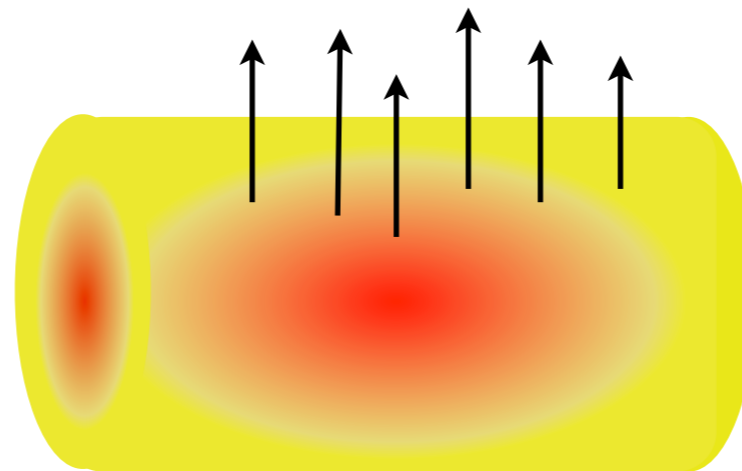
**NEAR SIDE: Fluid Cells Viscous Drag damps their relative motion and broadens correlations**

$$C(\Delta\eta) = \left\langle p_{t,1} p_{t,2} \right\rangle - \left\langle p_t \right\rangle^2$$

$C$

$\sigma_{\text{peripheral}}$

$\sigma_{\text{central}}$
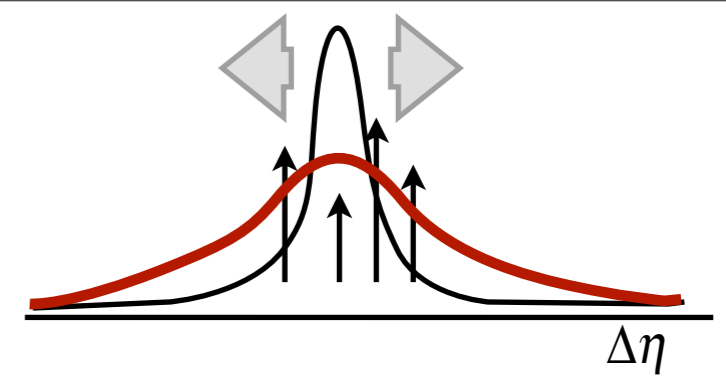
$\Delta\eta$

$$\nu = \frac{\eta}{T_c s}$$

$$\sigma^2 = \sigma_o^2 + 2\Delta V(\tau_f)$$

$$\Delta V(\tau) \equiv \left\langle (\eta - \langle\eta\rangle)^2 \right\rangle = \frac{2\nu}{\tau_o}\left(1 - \frac{\tau_o}{\tau}\right)$$

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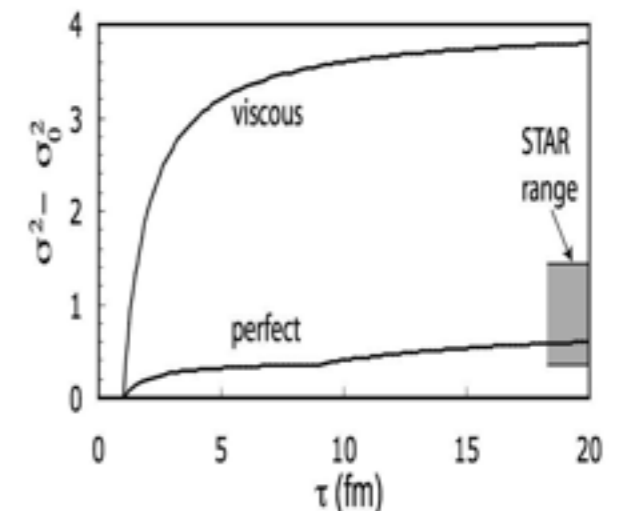
# This work: Differential $p_t$ $p_t$ Correlations

$$C(\Delta\eta, \Delta\varphi) = \frac{\left\langle \sum_{i=1}^{n_1} \sum_{j\neq i=1}^{n_2} p_{t,i} p_{t,j} \right\rangle}{\langle n_1 \rangle \langle n_2 \rangle} - \langle p_{t,1} \rangle \langle p_{t,2} \rangle$$

$$\Delta\eta = \eta_1 - \eta_2$$

$$\Delta\varphi = \varphi_1 - \varphi_2$$

$\Delta\varphi, \Delta\eta$

**Same side**

Inclusive average $p_t$: $\quad \langle p_{t,i} \rangle (\eta_i, \varphi_i) = \left\langle \sum_{k=1}^{n_1} p_{t,k} \right\rangle \bigg/ \langle n_i \rangle$

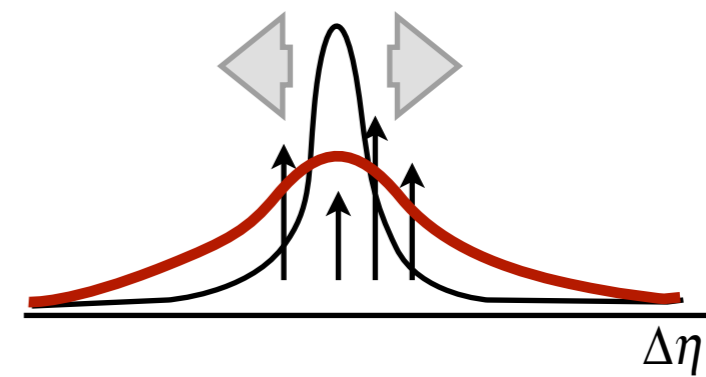Transverse momentum of particles in bin $i$: $\quad p_{t,i}$

Number of particles in bin $i$: $\quad n_i \equiv n_i(\eta_i, \varphi_i), \quad i = 1, 2$

**Broadening:** $\quad \sigma_c^2 \approx \sigma_0^2 + \sigma_{viscous}^2$

$$\sigma_{viscous}^2 = \frac{4\nu}{\tau_o} \left( 1 - \frac{\tau_o}{\tau} \right)$$

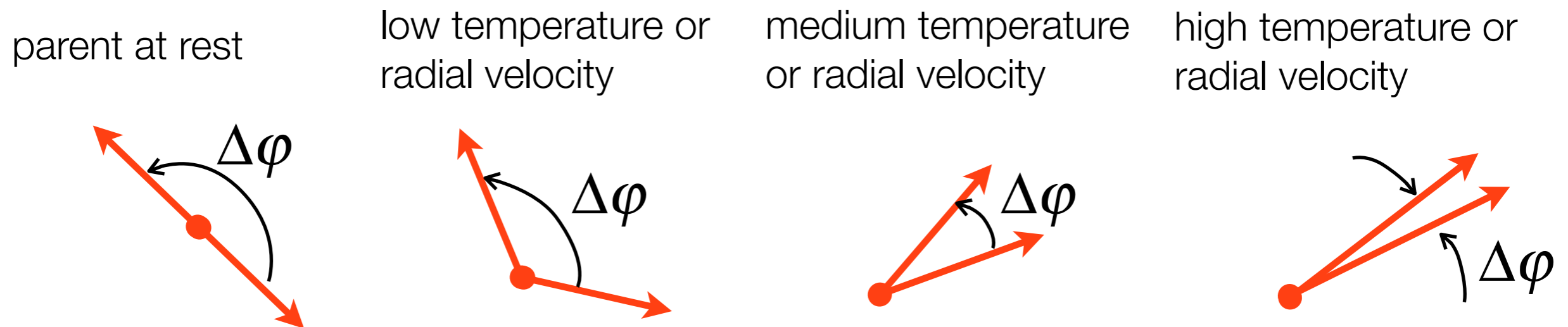Monday, June 7, 2010

# Theoretical/Physics Caveats



- The system temperature, viscosity, and Reynolds# vary through the lifetime of the collision system.

    - Measurement yields **time averaged quantities**

- Freeze out times from other data + model

- Other effects may contribute to the longitudinal shape of the correlation function

    - Decays, thermal broadening, jets, radial flow, CGC, etc

    - Jet expected to have minor impact in the momentum range considered in this analysis.

    - **Diffusion expected to dominate the broadening (see next few slides)**

- Detailed interpretation of the measurements requires collision models that provide comprehensive understanding of HI data.

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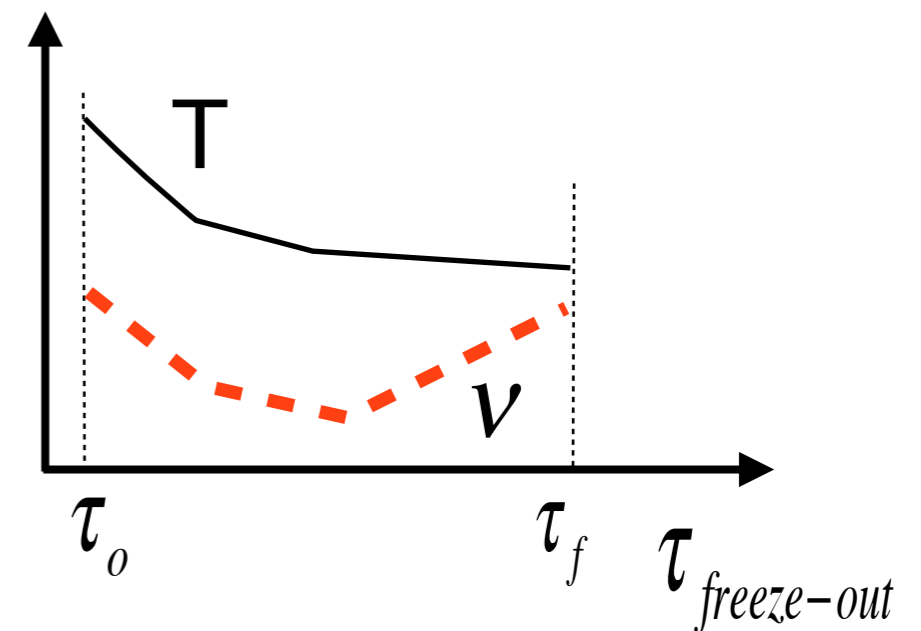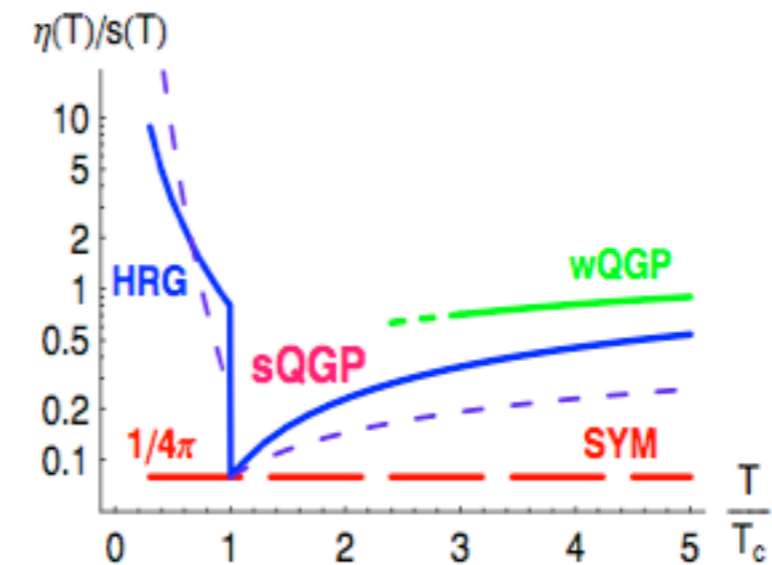
# Dynamical Effects (1): Resonance Decays

- An increase in system temperature and/or radial flow causes kinematical focusing of the decay products: ***narrowing of the correlation function***.

parent at rest

low temperature or radial velocity

medium temperature or radial velocity

high temperature or radial velocity

$\Delta\varphi$

$\Delta\varphi$
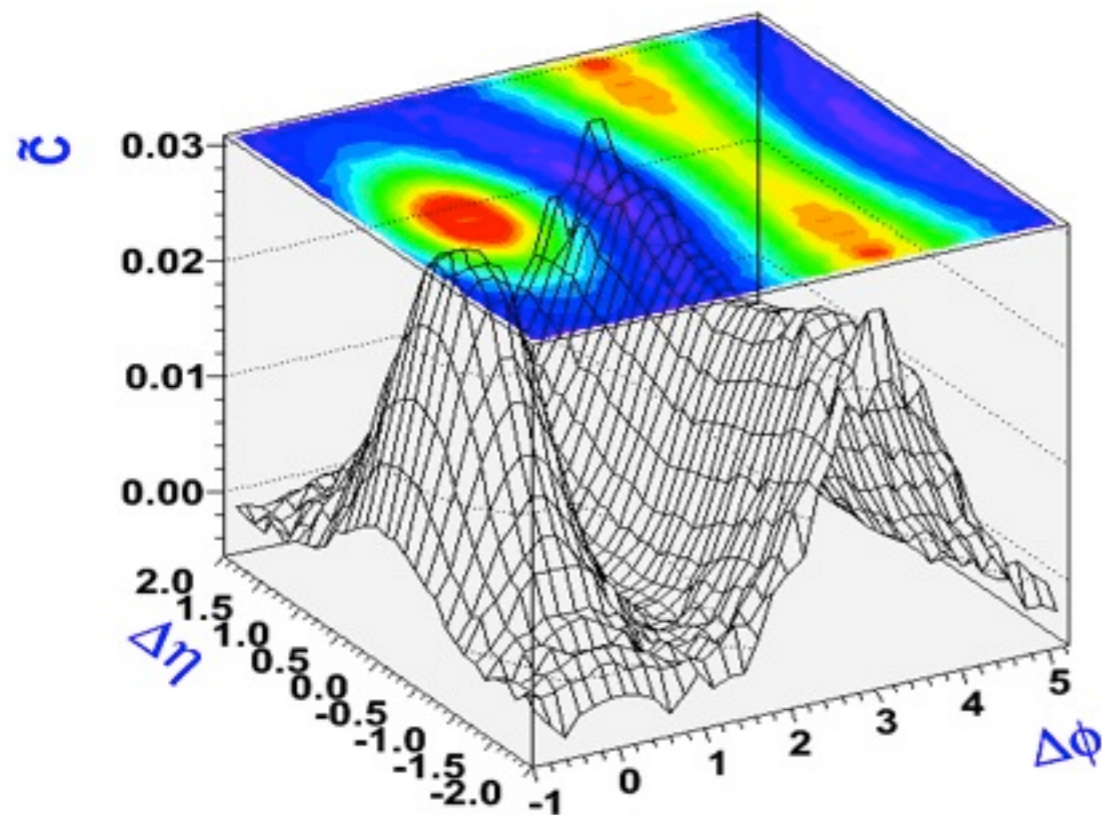
$\Delta\varphi$

$\Delta\varphi$

- Note however that re-scattering after decay implies causes ***thermal diffusion***, and ***correlation broadening***. --- needs modeling to properly assess its impact...
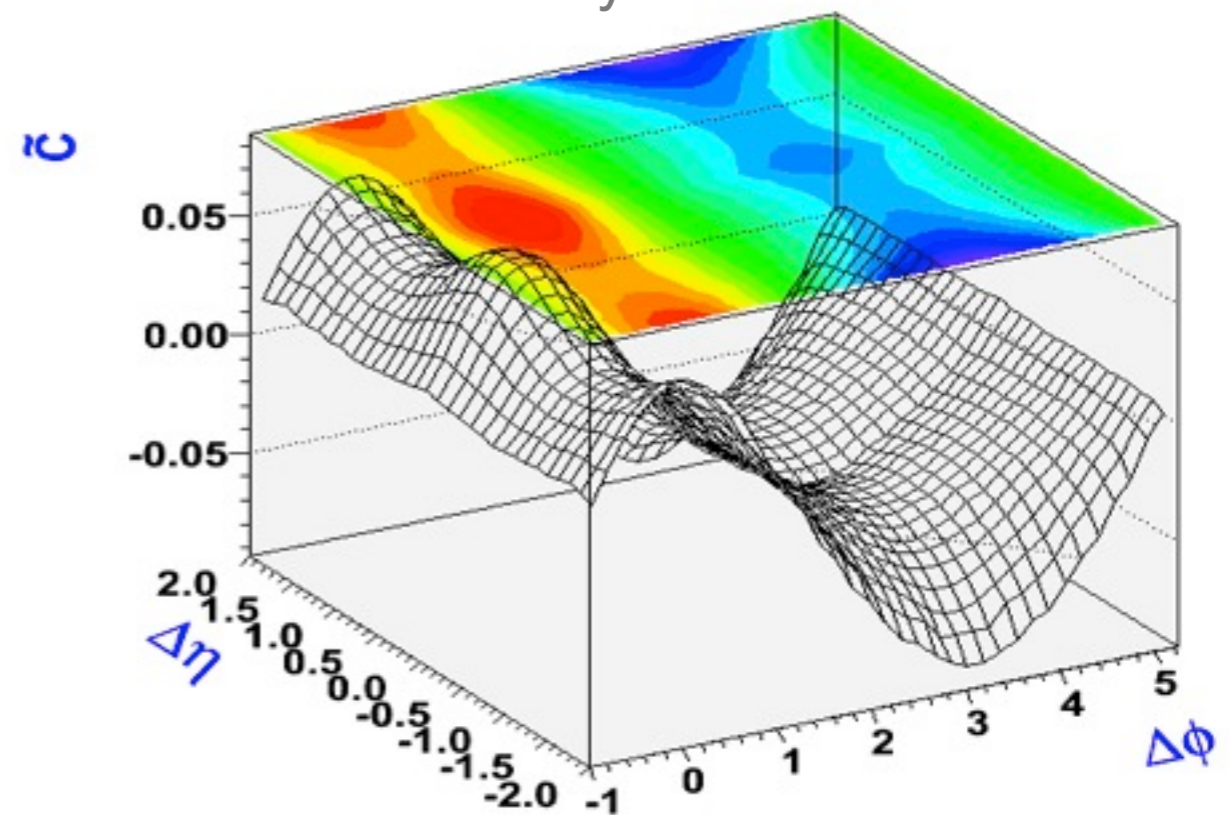
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# Dynamical Effects (2): Radial Flow

M. Sharma & C. A. Pruneau, Phys. Rev. C 79 (2009) 024905 for more details.

- Simulation based on PYTHIA p+p collisions at $\sqrt{s} = 200 \ GeV$

- Track kinematic cuts: $0.2 < p_T < 2.0 \ \text{GeV/c}$ and $|\eta| < 1$

"normal" PYTHIA events                    PYTHIA events radially boosted with v/c=0.3
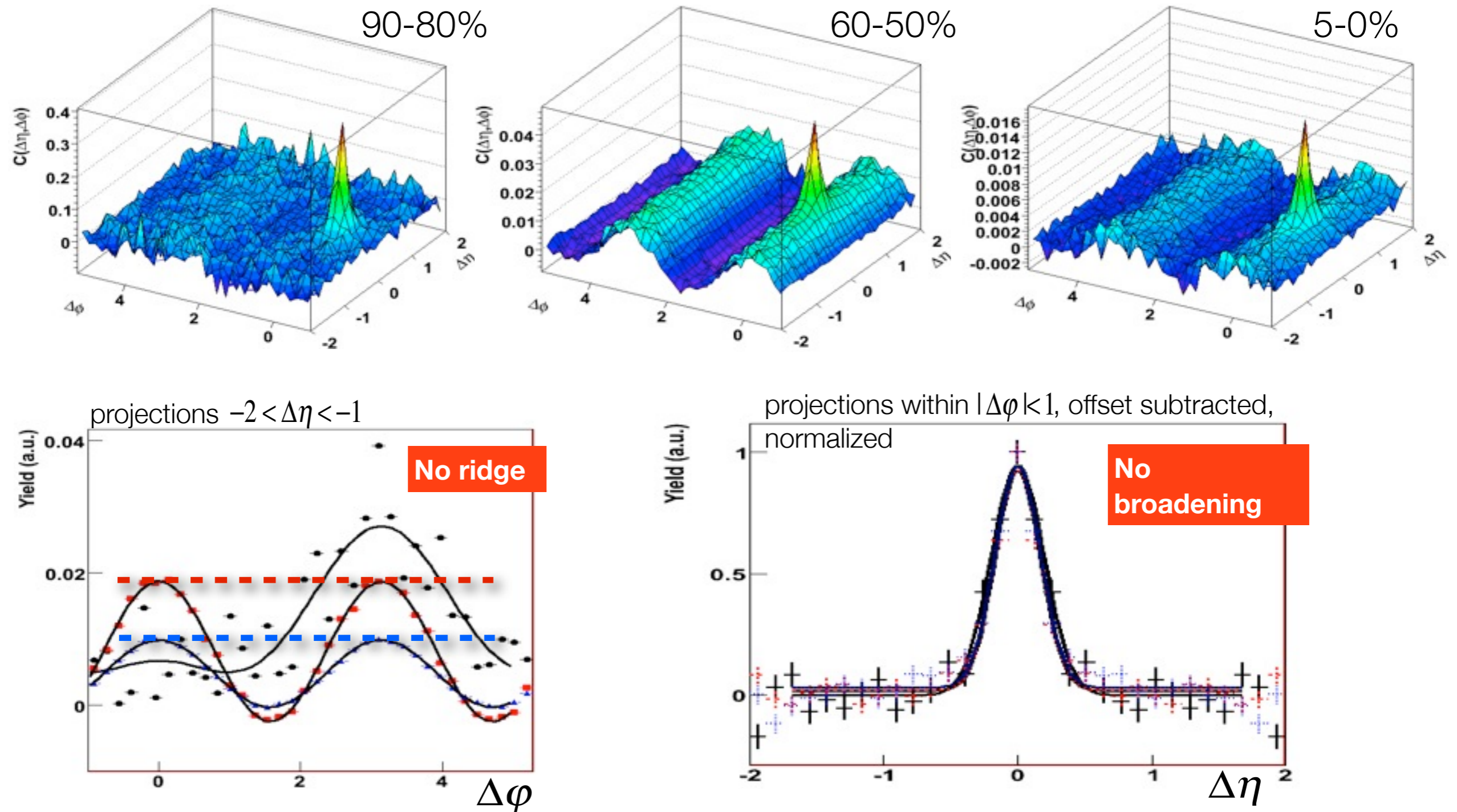


- Near-side kinematic focusing, formation of ridge-like structure with v/c>0
- Different shapes
- Narrowing of near side peak

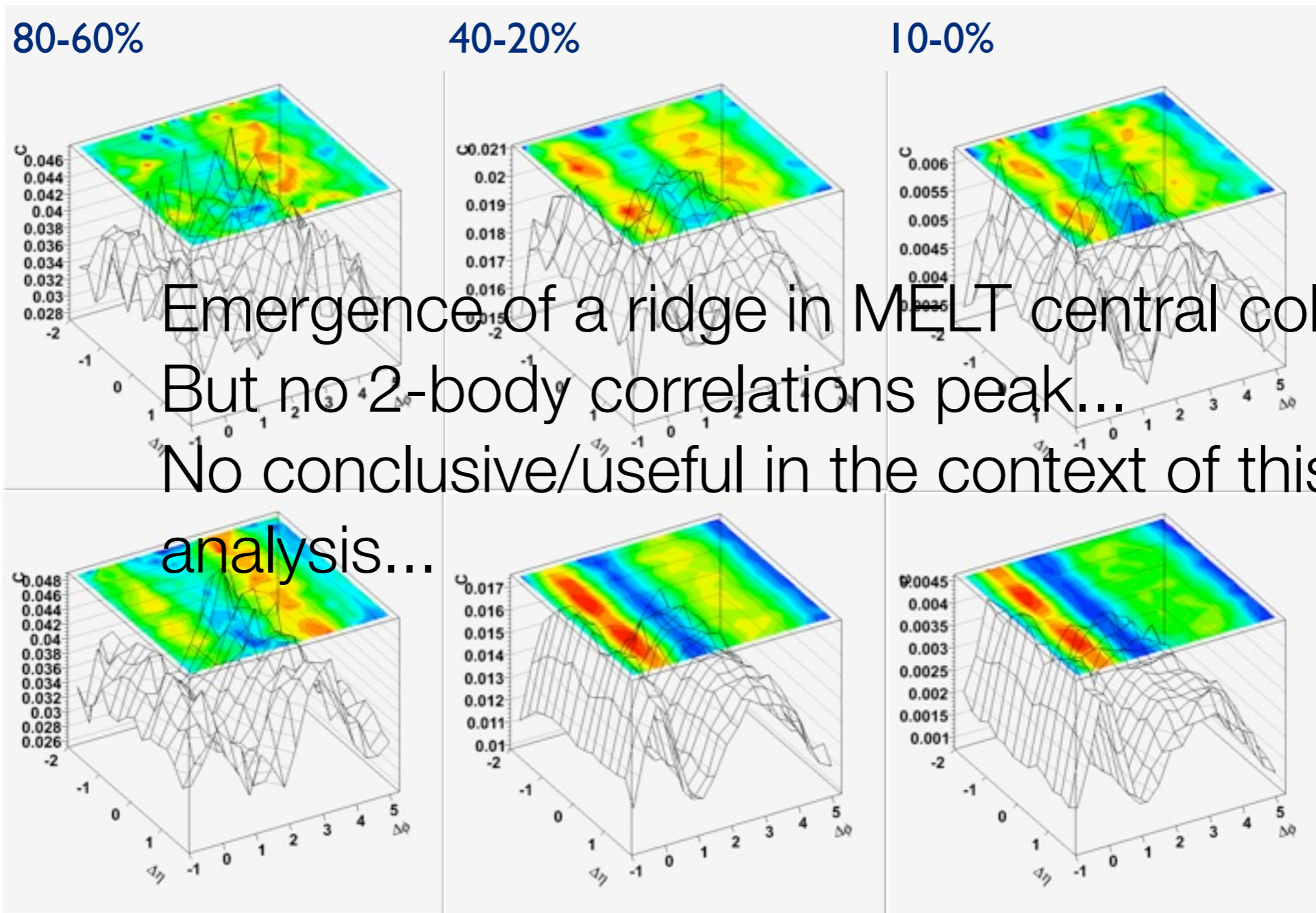S. A. Voloshin, arXiv:nucl-th/0312065; C. Pruneau, et al., Nuclear. Phys. A802, 107 (2008)

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# Dynamical Effects (3): Core vs Corona

**EPOS-1 (No HYDRO** ) simulation of Au Au @ $\sqrt{s_{NN}} = 200$ GeV



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# Dynamical Effects (4): AMPT (String Melting)

## Au+Au 200 GeV



Emergence of a ridge in MELT central collisions
But no 2-body correlations peak...
No conclusive/useful in the context of this
analysis...

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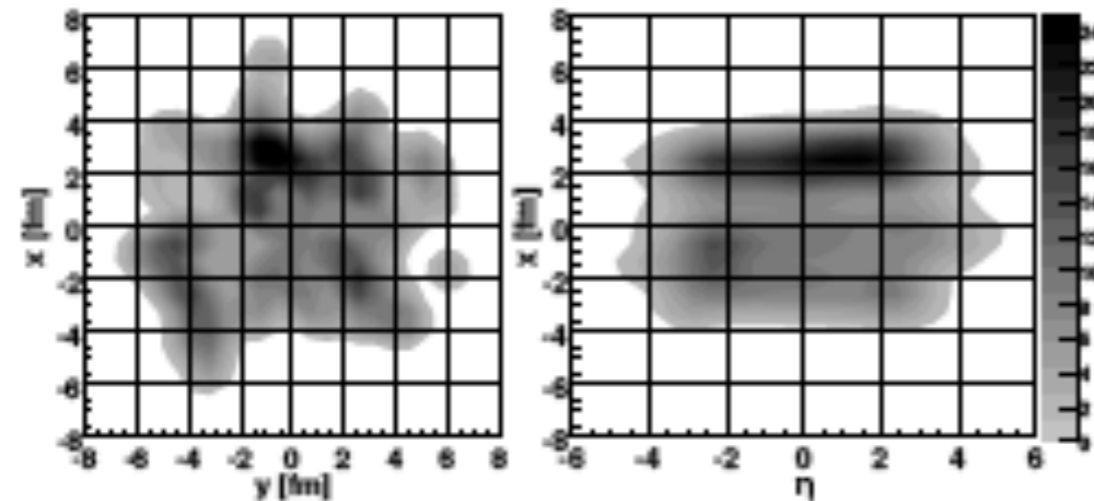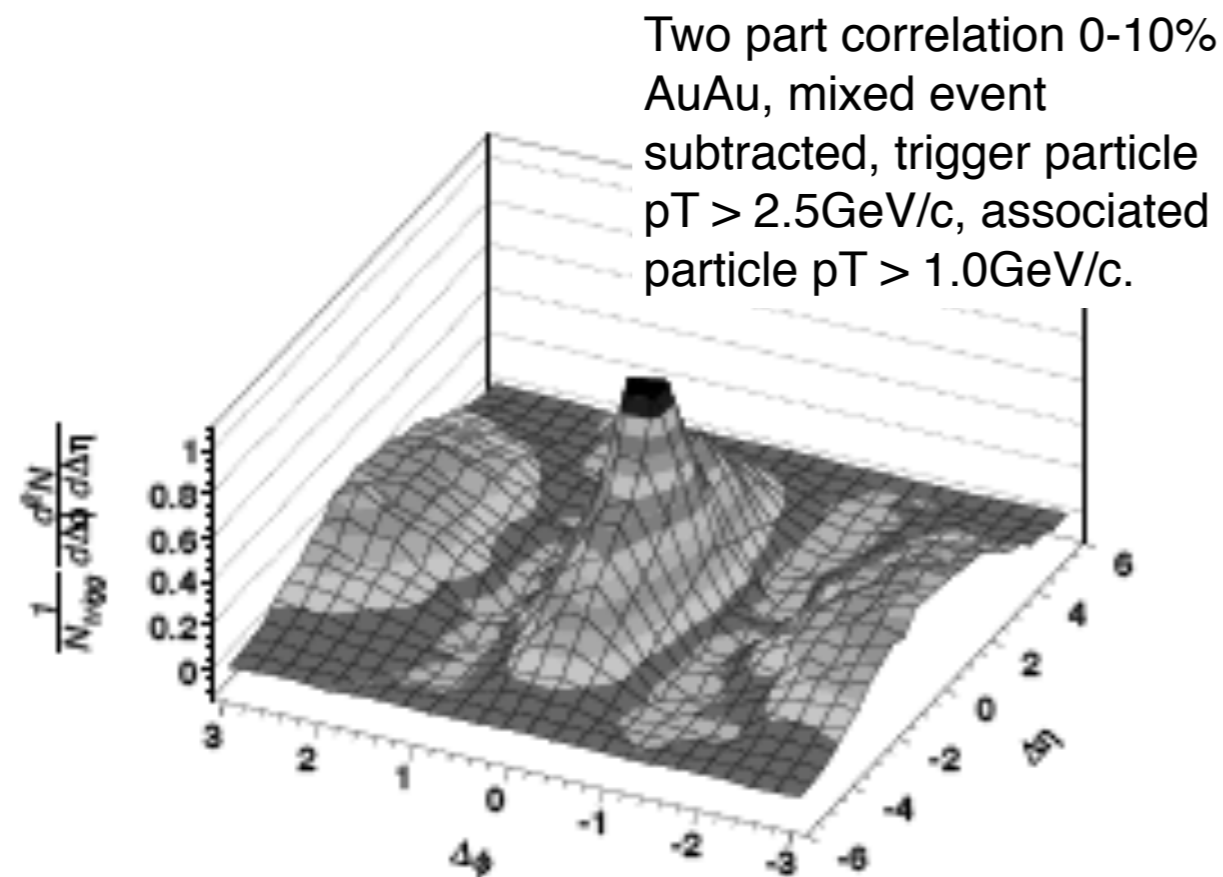
# Dynamical Effects (5): Initial Fluctuations (Nexus+Spherio)

J. Takahashi, et al., PRL103, 242301 (2009)

## Nexus: Fluctuating Initial Conditions; Spherio: 3D Hydro



Transverse & longitudinal profile of the initial energy density distribution (GeV/fm³) from NEXUS for 0-10% Au + Au @ 200GeV with centrality of top 10%.

**Smooth vs Fluctuation Initial Conditions**

Two part correlation 0-10% AuAu, mixed event subtracted, trigger particle pT > 2.5GeV/c, associated particle pT > 1.0GeV/c.

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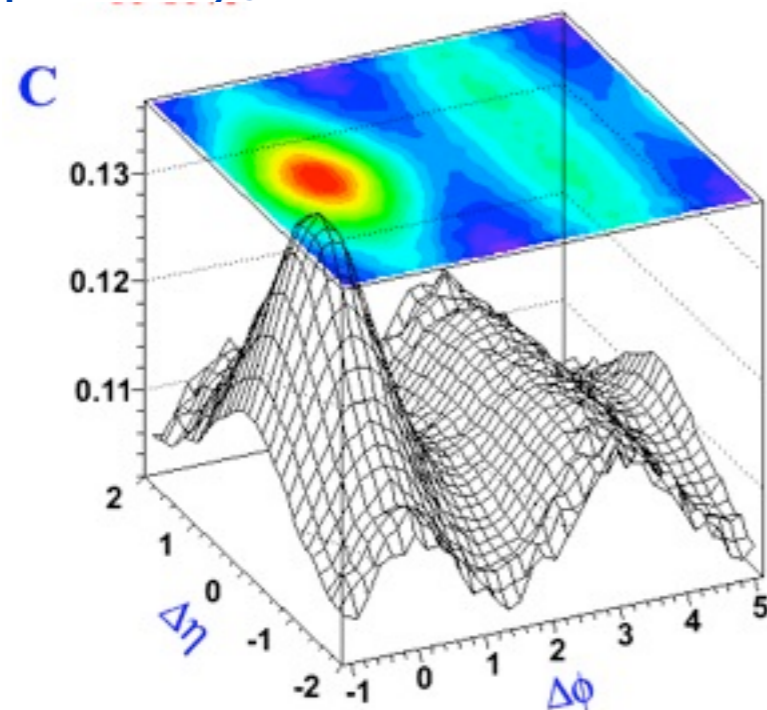
Monday, June 7, 2010
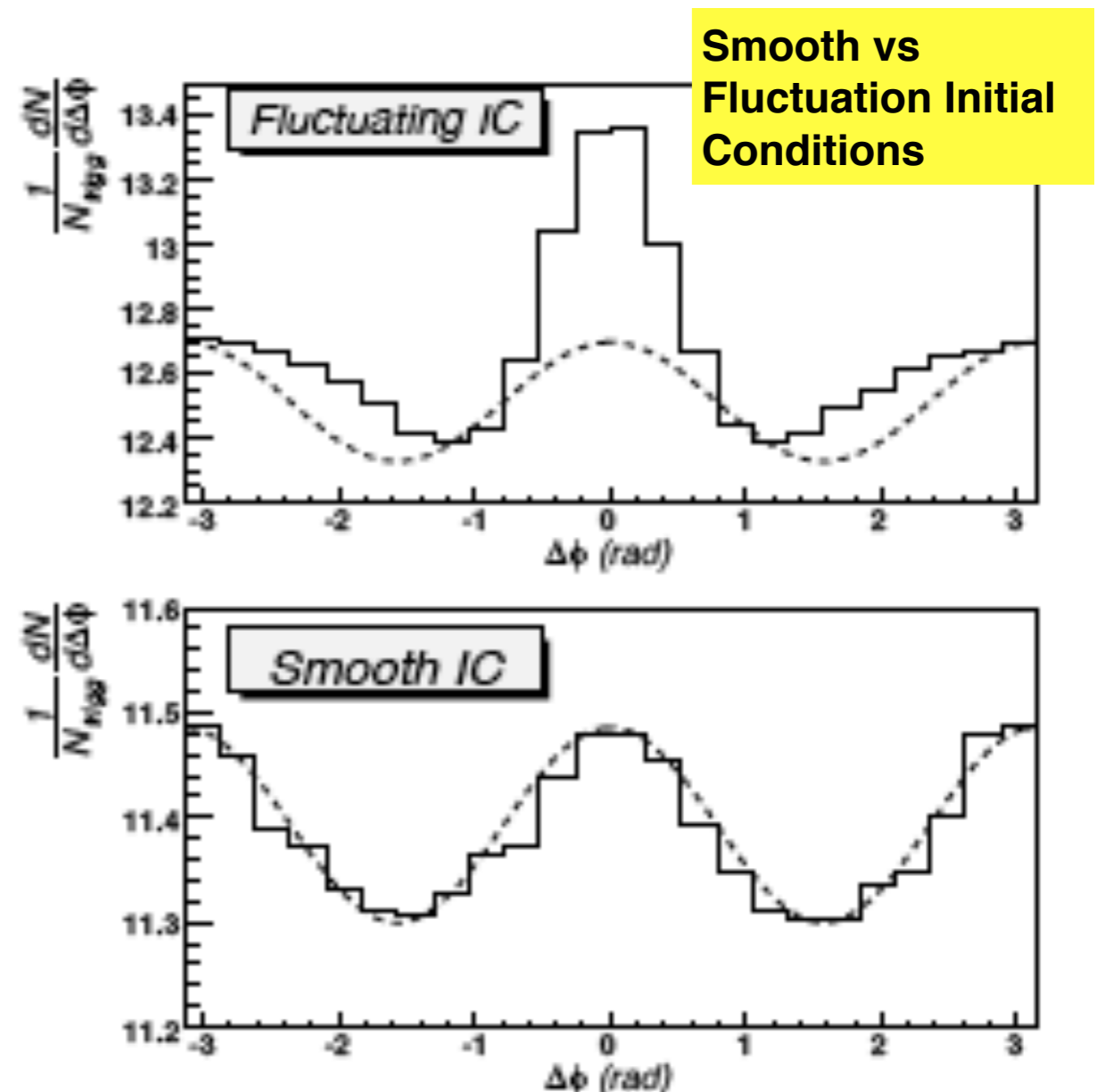
# Dynamical Effects (5): Initial Fluctuations (Nexus+Spherio)

**Nexus: Fluctuating Initial Conditions; Spherio: 3D Hydro**

Events provided by J. Takahashi
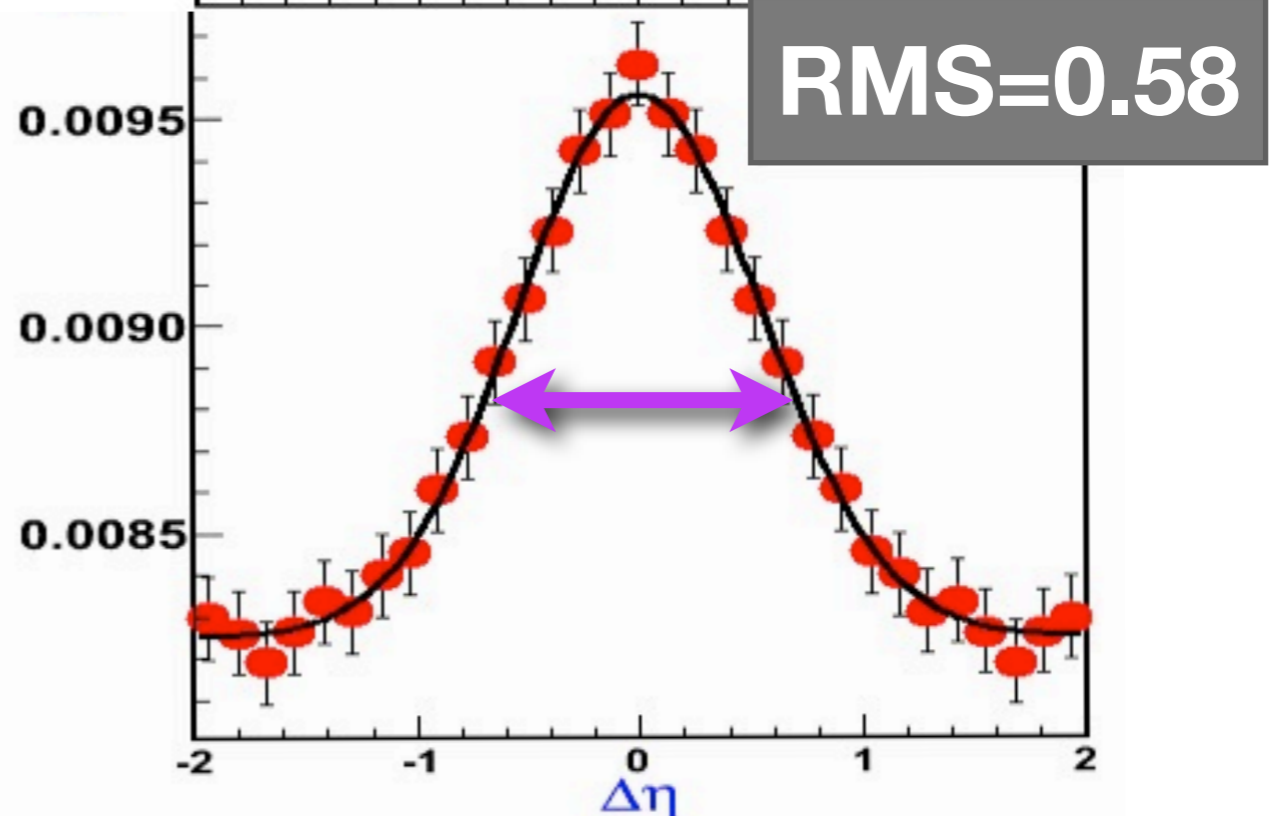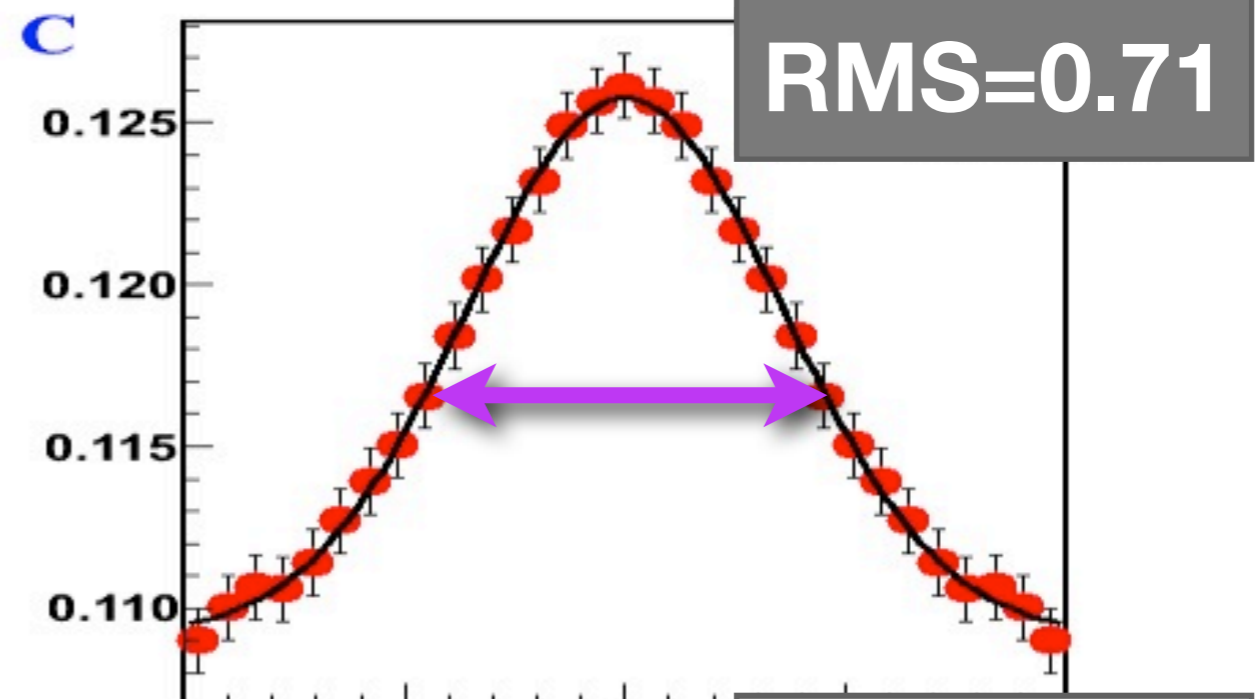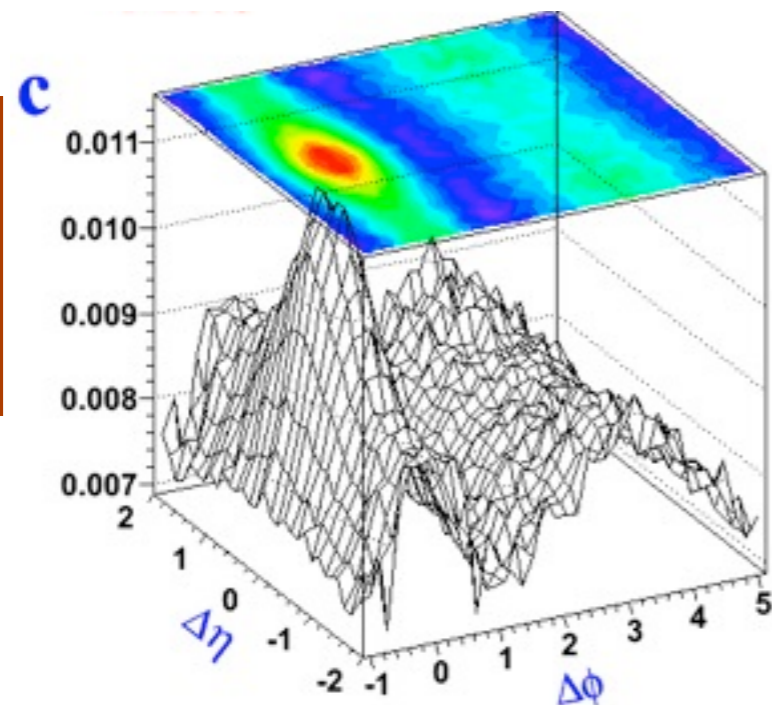


C. A. Pruneau, RHIC Users Meeting, June 7th, 2010.

# STAR Analysis: $p_t\ p_t$ Correlations

- Run 4 Au + Au sqrt($s_{NN}$) = 200 GeV, 8 M events, Minimum Bias Trigger

- Measure C and $R_2$ Correlation Functions (only showing C here)

- Measure Centrality Dependence vs $N_{part}$ based on Multiplicity in $|\eta| < 1$

- C and $R_2$ measured in
  - 2.5 cm z-vertex bins in range |z|<25 cm
  - Reverse/Forward magnetic field
  - Weighted average.

- Particles Kinematic Range ("Bulk" Particles)

    $$\eta < 1; \quad 0.2 < p_t < 2 \text{ GeV}$$

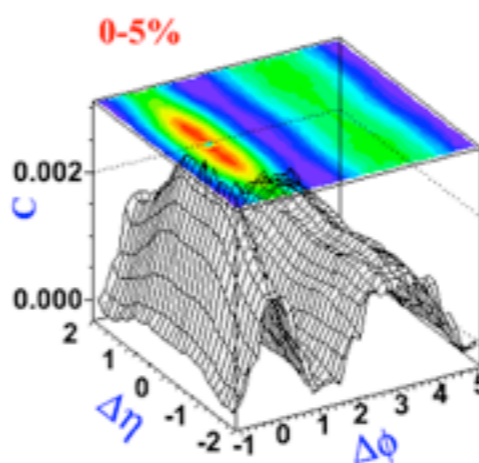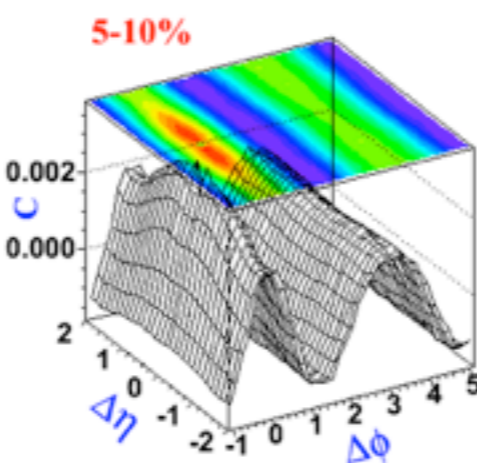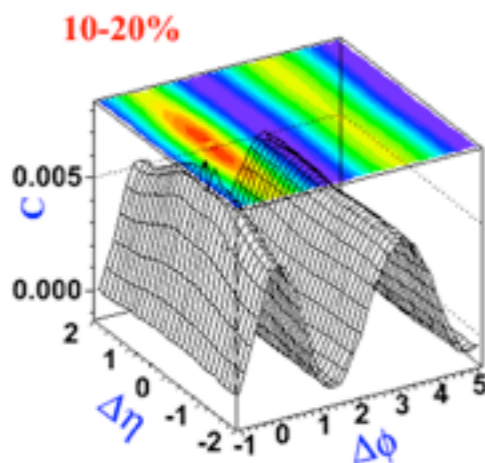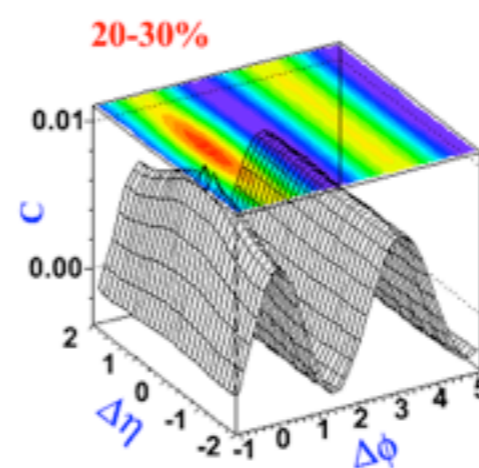- Standard STAR Track quality cuts.

- Merging corrections

$$R_2\left(\Delta\eta, \Delta\varphi\right) = \frac{\left\langle n_{pairs}\left(\Delta\eta, \Delta\varphi\right)\right\rangle}{\left\langle n\left(\eta_1, \varphi_1\right)\right\rangle\left\langle n\left(\eta_2, \varphi_2\right)\right\rangle} - 1$$

$$C\left(\Delta\eta, \Delta\varphi\right) = \frac{\left\langle \sum_{i=1}^{n_1}\sum_{j\neq i=1}^{n_2} p_{t,i}p_{t,i}\right\rangle}{\left\langle n_1\right\rangle\left\langle n_2\right\rangle} - \left\langle p_{t,1}\right\rangle\left\langle p_{t,2}\right\rangle$$

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# Results: $C(\Delta\eta, \Delta\varphi)$

**Peripheral**



70-80%

60-70%

50-60%

40-50%

30-40%

20-30%

10-20%

5-10%

0-5%
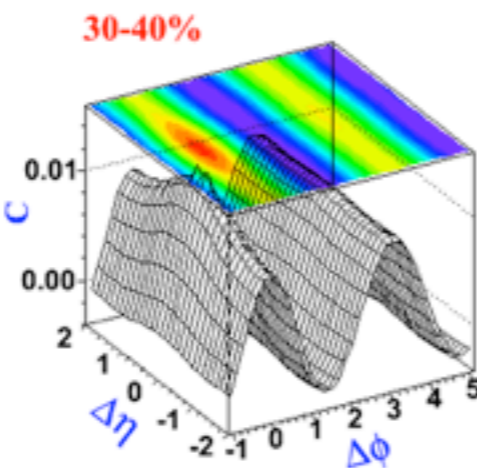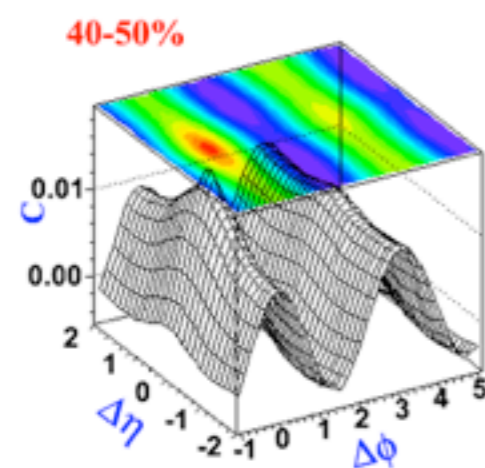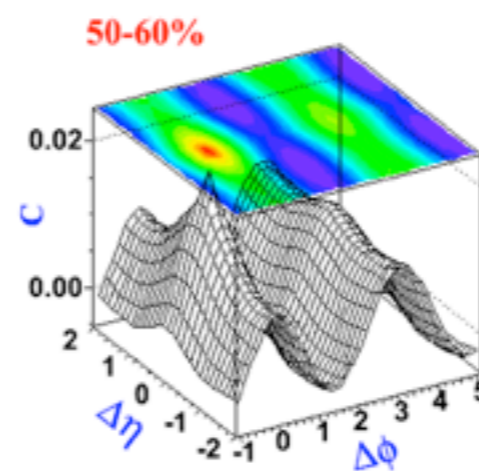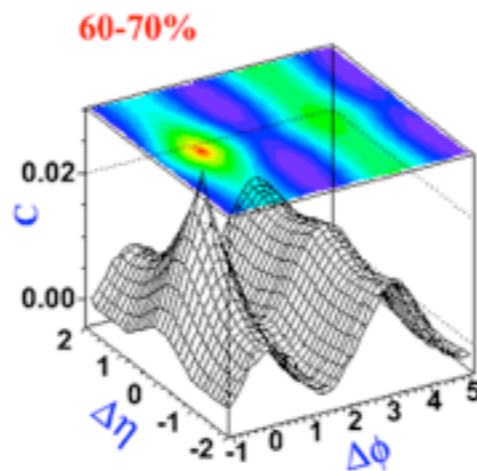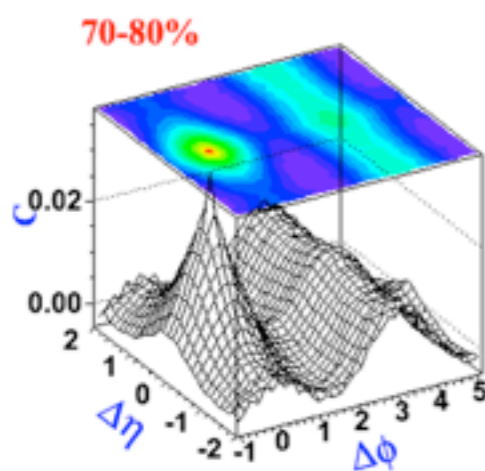
**Central**

- Peripheral Collisions
  - Prominent near side peak
  - Ridge-like structure on away-side (momentum conservation)
- Strong elliptic flow component in mid-central collisions.
- As $N_{part}$ increases
  - Monotonic reduction of amplitude
  - Emergence of a near side ridge.
  - Progressive elongation of the near side peak

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# Results: $C(\Delta\eta, \Delta\varphi)$



(a) 70-80%    (b) 30-40%    (c) 0-5%
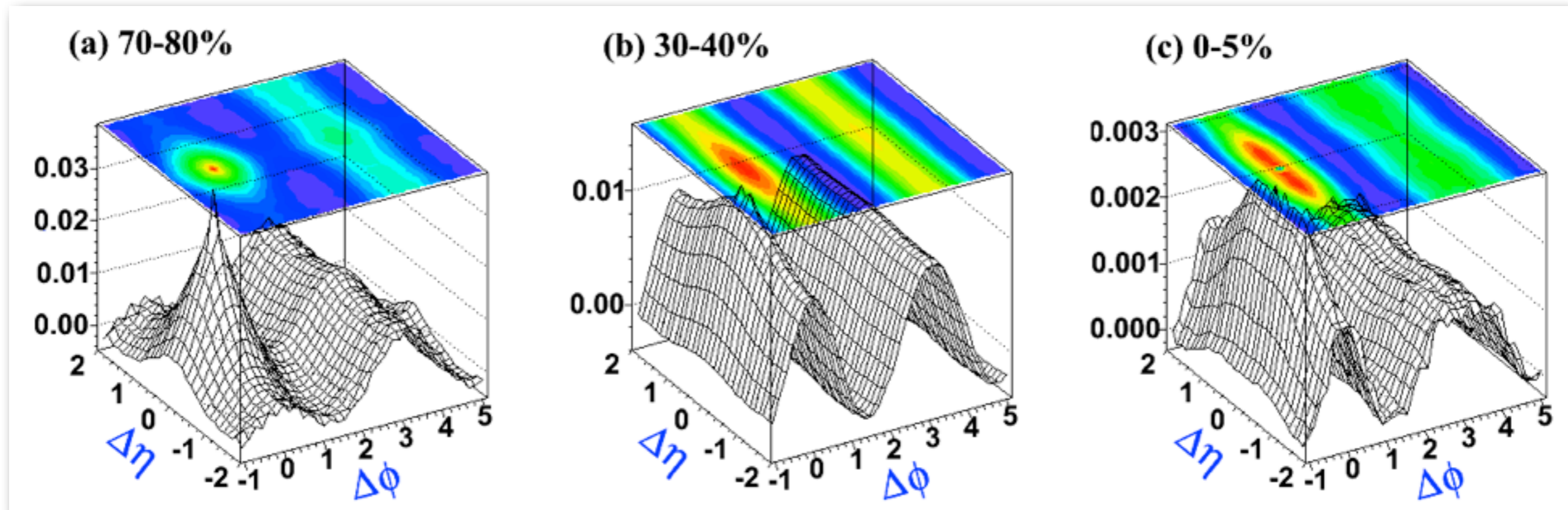
- Peripheral:
  - "Narrow" near-side peak; broad ($\Delta\eta$) away side elongated structure.
- Mid-Central:
  - Strong flow-like signal (v2); broadening of near-side peak at $\Delta\eta \approx \Delta\varphi \approx 0$
- Central:
  - Further broadening of near-side peak and ridge structure

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# Results: $C\left(\Delta\eta, |\Delta\varphi| < 1\right)$

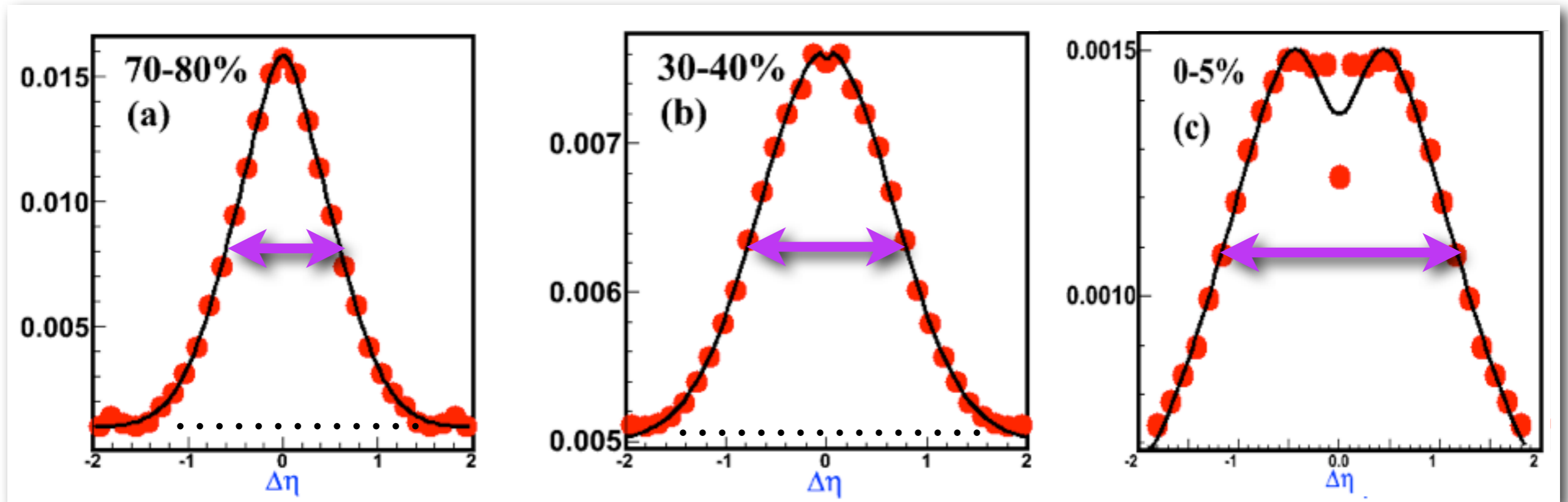**NEAR SIDE: Fluid Cells Viscous Drag damps their relative motion and broadens correlations**



- Correlation Function is not Gaussian

- Characterize width as RMS of the distribution above "pedestal"

- Determine pedestal (offset) based on fit of the line shape

$$b + a_n \exp(-\Delta\eta / 2\sigma_n^2) + a_w \exp(-\Delta\eta / 2\sigma_w^2)$$

- Subtract offset; Set $\Delta\eta = 0$ point equal to neighboring points in 0-5%; Calculate RMS from data, but include $|\Delta\eta| > 2$ extrapolation from fit.

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# Results: $C\left(\Delta\eta, |\Delta\varphi| < 1\right)$
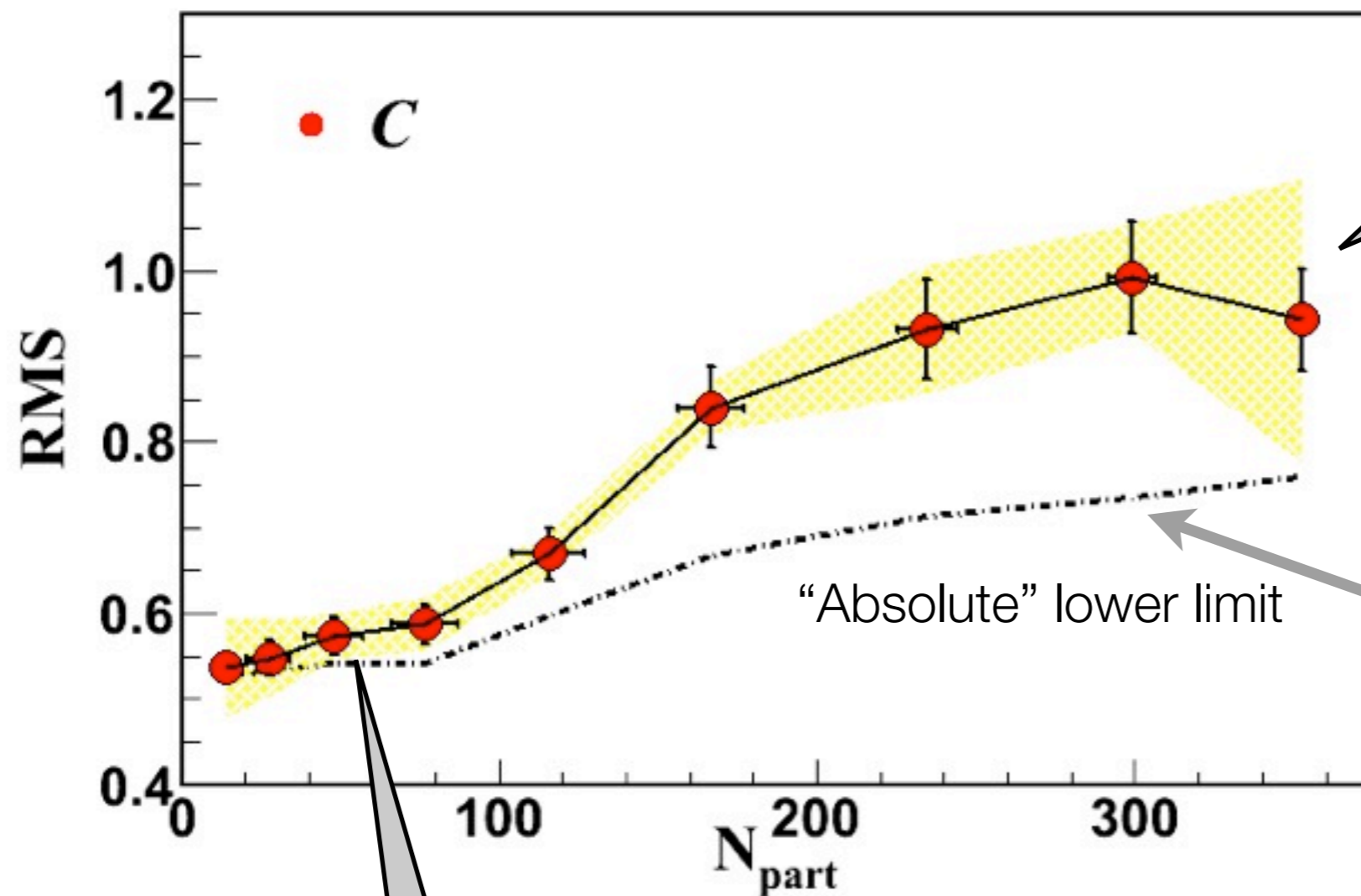


Saturation?
Next slide for systematic errors discussion

"Absolute" lower limit

30-40%
(b)

Slow rise with increasing Npart
- Incomplete thermalization
- Radial flow effects
- Offset/Background shape - centrality selection effects
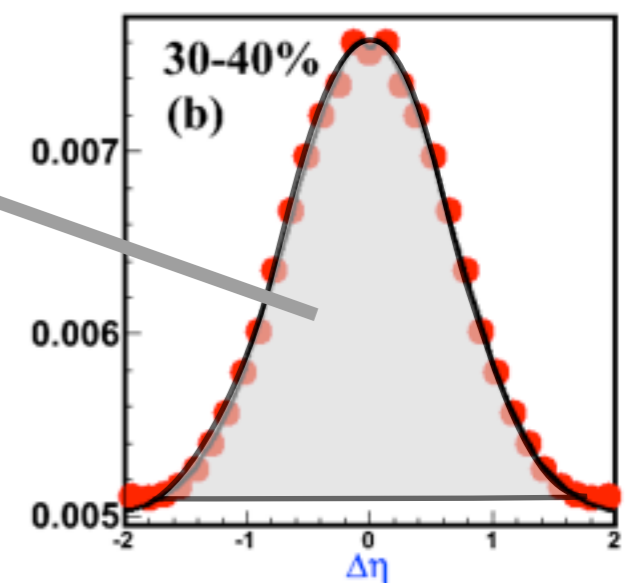
# Systematic Errors:

- Physics Backgrounds or Dynamical Effects
  - Contributions from non-primary tracks (e.g. weak decays): negligible
  - Contributions from photon conversions: negligible
  - Broadening vs $N_{part}$ weakest at low $N_{part}$ where radial flow grows fastest.
  - Radial flow induced narrowing, etc.
- Observable is robust to first order but ...
  - pt efficiency dependence
  - z-vertex bin and field direction dependencies
  - TPC occupancy
  - Offset determination and extrapolation to $\left|\Delta\eta\right| > 2$
- Evaluate sys. errors based on width differences between forward vs. reverse fields, z-vertex dependence.

# Shear Viscosity/Entropy:

Based on Gavin and Abdel-Aziz, Phys.Rev.Lett. 97 (2006) 162302; nucl-th/0606061 (2006)

Viscous broadening: $\sigma^2_{viscous} = \dfrac{4\nu}{\tau_o}\left(1 - \dfrac{\tau_o}{\tau}\right)$     $\nu = \dfrac{\eta}{T_c s}$

Measured broadening: $\begin{aligned} & RMS: 0.55 \to 0.94 \\ & \Delta\sigma^2 \simeq \sigma^2_{viscous} = 0.58 \pm 0.28 \end{aligned}$

Assume Temperature: $T_c = 170 \text{ MeV}$

Formation Time (th. syst.): $\tau_o = 1^{+0.5}_{-0.4}$

Freeze-out Time (central): $\tau = 10 - 20 \text{ fm/c}$     Range defines theory systematic errors

Shear Viscosity/Entropy: $\eta/s = 0.14 \pm 0.02(\text{stat}) \pm 0.06(\text{meas syst.})$

$\pm 0.14(\text{theory syst.})$

Shear Viscosity/Entropy - Upper limit: $\eta/s^{\max} = 0.2 + 0.14(\text{theory syst.})$

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# Summary

- Goal: Measurement of shear viscosity (per unit entropy) based on new observable, C, in Au + Au collisions at 200 GeV.

  - $C(\Delta\eta)$ expected to broaden with increasing system lifetime, i.e. increasing large $N_{part}$ (central collisions).

- Considered various dynamical effects/models that contribute to the structure of C.

  - Expect viscous diffusion to dominate correlation broadening.

- Measured $C(\Delta\eta, \Delta\varphi)$ vs collision centrality.

  - Observed changes vs centrality qualitatively similar those observed for other correlation functions.

  - Significant near-side peak broadening.

- Shear Viscosity/Entropy:  $\eta/s = 0.14 \pm 0.02(\text{stat}) \pm 0.06(\text{meas syst.})$

  - Upper limit: $\pm 0.14(\text{theory syst.})$

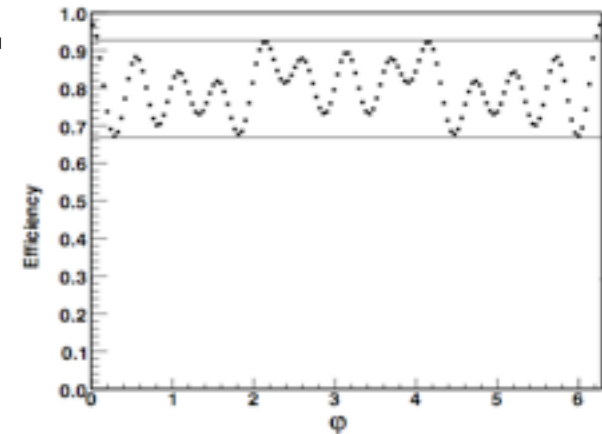$$\eta/s^{\text{max}} = 0.2 + 0.14(\text{theory syst.})$$

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C. A. Pruneau, RHIC Users Meeting, June 7th, 2010.

Monday, June 7, 2010

# Extra Slide(s)
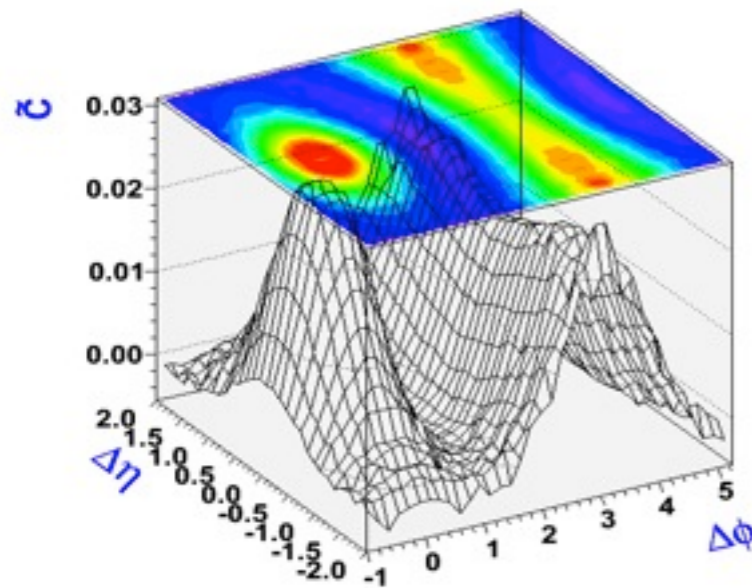
# Experimental Caveat:  Observable Robustness(?)

**Study with PYTHIA, p+p collisions at** $\sqrt{s} = 200$ **GeV**

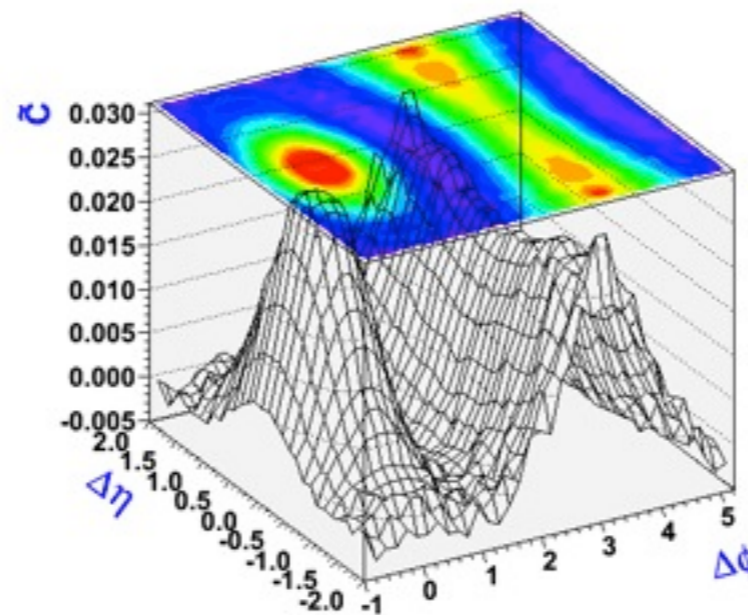**Twelve fold angular efficiency dependence, and linear dependence on pT**

$$\varepsilon(\varphi, p_\perp) = \varepsilon_0 \left(1 - ap_\perp\right)\left[1 + \sum_{n=1}^{12} \varepsilon_i \cos(n\varphi)\right]$$
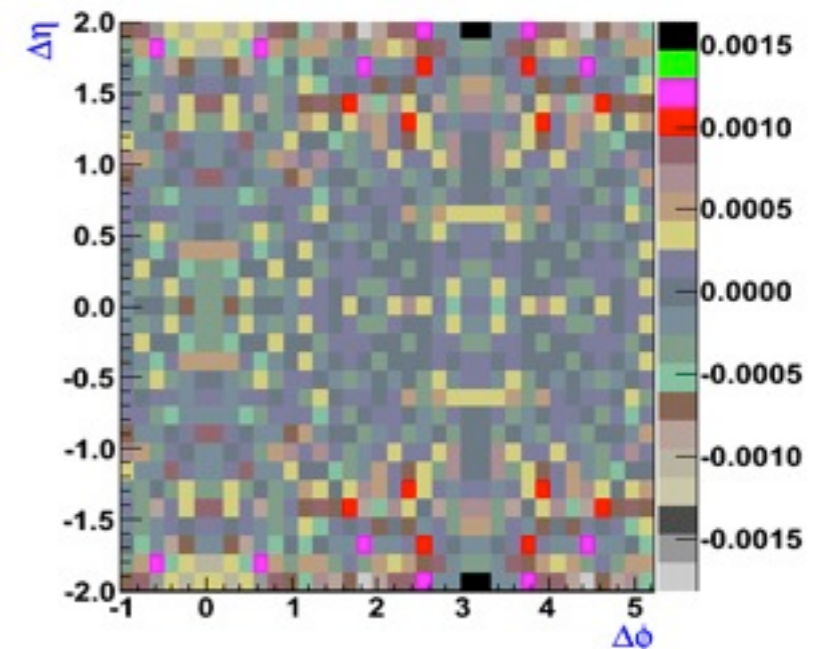
$\varepsilon_o$=0.8, a =0.05

**Efficiency = 100%**

**Efficiency = 80%**

**Difference**

Statistical error = 0.001, difference = 0.0005 => Robust
Observable if efficiency has small dependence on pt.

**In practice, a measurement 'near' detection threshold in $p_t$, implies the observable is not perfectly robust (Simulation in progress)**